

Real traffic-data based evaluation of vehicular traffic environment and state-of-the-art with future issues in location-centric data dissemination for VANETs[☆]

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ABSTRACT

Extensive investigation has been performed in location-centric or geocast routing protocols for reliable and efficient dissemination of information in Vehicular Adhoc Networks (VANETs). Various location-centric routing protocols have been suggested in literature for road safety ITS applications considering urban and highway traffic environment. This paper characterizes vehicular environments based on real traffic data and investigates the evolution of location-centric data dissemination. The current study is carried out with three main objectives: (i) to analyze the impact of dynamic traffic environment on the design of data dissemination techniques, (ii) to characterize location-centric data dissemination in terms of functional and qualitative behavior of protocols, properties, and strengths and weaknesses, and (iii) to find some future research directions in information dissemination based on location. Vehicular traffic environments have been classified into three categories based on physical characteristics such as speed, inter-vehicular distance, neighborhood stability, traffic volume, etc. Real traffic data is considered to analyze on-road traffic environments based on the measurement of physical parameters and weather conditions. Design issues are identified in incorporating physical parameters and weather conditions into data dissemination. Functional and qualitative characteristics of location-centric techniques are explored considering urban and highway environments. Comparative analysis of location-centric techniques is carried out for both urban and highway environments individually based on some unique and common characteristics of the environments. Finally, some future research directions are identified in the area based on the detailed investigation of traffic environments and location-centric data dissemination techniques.

1. Introduction

The Internet Engineering Task Force (IETF) predicted the wide use of the Global Positioning System (GPS) in 1996. Several experiments were performed by the IETF to integrate the GPS into the Internet protocols. Based on these experiments, the IETF suggested in its internet-Drafts a family of protocols and addressing methods to integrate the GPS into communication protocols in its Internet Draft. The Internet-Drafts also provide future visualization of various location-based services such as emergency message multicasting in a specific geographical region, server-client based services inside a geographic range, and service advertisement in restricted range,

location-based continuous information service for mobile users, and traffic management [1].

Ad hoc networks, wireless Local Area Networks (LAN) and cellular telephony coevolved into a new research area known as VANETs. The solutions for most of the traffic-related problems can be provided by using VANETs as a potential platform for various Intelligent Transport Systems (ITS) applications [2,3]. Owing to its potential in solving traffic problems, researchers from industries and academia are considering VANETs as an important topic in transportation research. Traffic safety is one of the major goals of VANETs [4,5]. Possibilities of comfort applications are also being explored [6–9]. Green computing is another important goal of VANETs [10]. Features that distinguish VANETs

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from other kinds of ad hoc networks are the hybrid architecture of vehicular networks, high mobility of vehicles, freedom from the limitation of battery life, processor's computational power and platform for various infotainment applications [11]. The operational cost of ITS applications which using VANETs as a platform for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications are significantly lower than that of specific hardware-based applications. Owing to this lower cost of operation, research organizations in industry and government are working on VANETs for enhancing safety and reducing congestion in on-road traffic. A variety of state-of-the-art equipments are being incorporated in vehicles as their on-board units for facilitating efficient communications among vehicles and Road Side Units (RSUs). These equipment includes display screens, sensors, antennas, cameras, and radars. Incorporation of these equipments is vital for providing on-road safety and user comfort during travel [12–15].

Enhancing reliability and efficiency in vehicular information dissemination is a fundamental research problem for researchers in VANETs [16,17]. Recently, geocast routing has gained significant attention of researchers of information dissemination, which were predicted long before by the IETF [18–21]. The reason behind the preference is the suitability of geocast routing in for disseminating information to a group of vehicles moving on-road and sharing a specific geographical region. In most ITS applications, traffic-related information is required to be disseminated to all vehicles moving on-road and sharing a specific geographical region. Geocast routing empowers researchers to develop location-based services in vehicular traffic environments [22]. The idea of geocast routing in VANETs originated from the theme of multicast routing in ad hoc networks. In multicast routing, information is disseminated from a single source to a specified number of receivers in a group (cf. Fig. 1) [23]. In geocast routing, traffic information is disseminated from a single source vehicle to all the vehicles of a group within a geographical region (cf. Fig. 2). The group of vehicles sharing a specific geographical region and destined for traffic information is known as Zone of Relevance (ZOR) in geocast routing [24].

The impact of on-road traffic environments on the performance information dissemination is vital in vehicular ad hoc networks [64]. Therefore, in this paper vehicular traffic environments are classified into three categories, namely urban, highway, and rural traffic environments. This classification is based on the identification of several differentiating characteristics for each of the three categorized vehicular traffic environments. Physical parameters of on-road traffic such as the Vehicle Distance Travelled (VDT), traffic volume, Inter-Vehicle Distance (IVD), speed, lane occupancy, and traffic variability were analyzed for each of the three categories of traffic environments using on-road real time-traffic data. The analysis includes month and year wise distribution of VDT, hour wise distribution of traffic volume, and hour wise distribution of IVD in a day. The impact of weather conditions on traffic environments is analyzed considering the reductions in traffic volume, traffic capacity and speed of freeway traffic. The analysis leads to the division of on-road weather conditions into three types, namely rain, storm, and fog based on their differentiating characteristics. Protocol design challenges are discussed considering

the impact of physical parameters and weather conditions on vehicular traffic environments. Further, geocast routing protocols are investigated by being classified into urban-centric or highway centric protocols and the Next Hop Vehicle (NHV) or flooding based forwarding techniques. In this investigation, each geocast routing protocol is precisely studied in terms of functional and qualitative characteristics along with their pros and cons. Based on this investigation, a comparative analysis of variously considered geocast routing protocols is carried out. Finally, a number of open research challenges in information dissemination in VANETs are discussed at the end of this article for researchers' attention in near future.

The rest of the paper is organized as follows. Section 2 analyzes vehicular traffic environments based on real traffic data. State-of-the-art of location-centric data dissemination in terms of critical qualitative evaluation is presented in Section 3. Open research challenges in information dissemination in VANETs are discussed in Section 4. Conclusion of the study is presented in Section 5.

2. Vehicular traffic environment

VANETs have been considered as one of the most dynamic networks in terms of communication environments. Because of the highly dynamic traffic environments, the performance of any geocast routing protocol completely depends on the protocol's adaptability to traffic environments [25]. Therefore, an inspective analysis of traffic environment has been performed, and is presented in the next section. The traffic environment analysis has three sections. In the first section, classification of vehicular traffic environments based on physical characteristics has been explained. Real time traffic data has been analyzed for various physical parameters of vehicular traffic environments in the second section. In the third section, the impact of weather conditions on vehicular traffic environments has been explored.

2.1. Classification of traffic environments

Traffic environments in VANETs have been classified into three categories: urban, highway, and rural. Each of the categories has distinguishable characteristics. The knowledge of characteristics of each of these categories would be an advantage during the development of geocast routing protocols for a specific traffic environment. The characteristics of each of the vehicular traffic environment categories have been visualized in Fig. 3.

2.2. Analysis of physical parameters using real traffic data

The dynamics of physical parameters of highly unstable vehicular traffic environments is one of the key factors to be considered in the analysis of geocast routing protocols. In recently suggested geocast routing protocols, researchers have given importance to physical parameters of traffic environment while designing geocast routing protocols. Therefore, physical parameters have been empirically analyzed by using real traffic data from the California Vehicle Activity Database (CalVAD) [26] and US Department of Transportation [27]. The physical parameters considered for empirical analysis are VDT, traffic volume, IVD, speed, lane occupancy, and traffic variability.

Traffic volume has a significant impact on the performance of geocast routing protocols. A high traffic volume on a road network results in information overload whereas a low traffic volume causes network disconnection. Traffic volume follows rapid changes in urban and rural traffic environments as compared to the highway traffic environment.

In Fig. 4, the real data of VDT are shown. Fig. 4(a) shows the year wise increment in VDT. A rapid growth in VDT from 1989 to 2008 and a moderate growth from 2009 onwards can be clearly observed. The data shown in Figs. 4(b), (c), and (d) are daily VDT in urban, rural, and highway traffic environments respectively. It can be clearly observed that the VDT continuously increases from January to June and

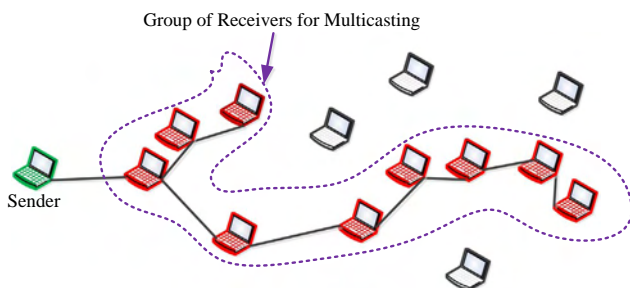


Fig. 1. An example of multicast routing in ad hoc networks.



Fig. 2. An example of geocast routing in realistic vehicular ad hoc networks.

decreases till December in each of the three traffic environments considered. The difference in VDT for different months can be attributed to the environmental changes in US and the public events. It is considered that because of the starting of normal weather, VDT increases with the starting months of a year. During the year-end period, VDT decreases owing to the impact of winter when less public events are organized. The highest volume and range of daily VDT is

higher in urban traffic environment as compared to rural and highway traffic environment. The highest volume of VDT in the urban traffic environment is 5.7 billion miles where as it is approximately 3 billion miles and 5 billion miles for rural and highway environments, respectively. The range of VDT in the urban traffic environment is 5–5.8 billion miles where as it is approximately 2.3–3 billion miles and 4.4–5 billion miles for rural and 4.4–5 billion miles for highway.

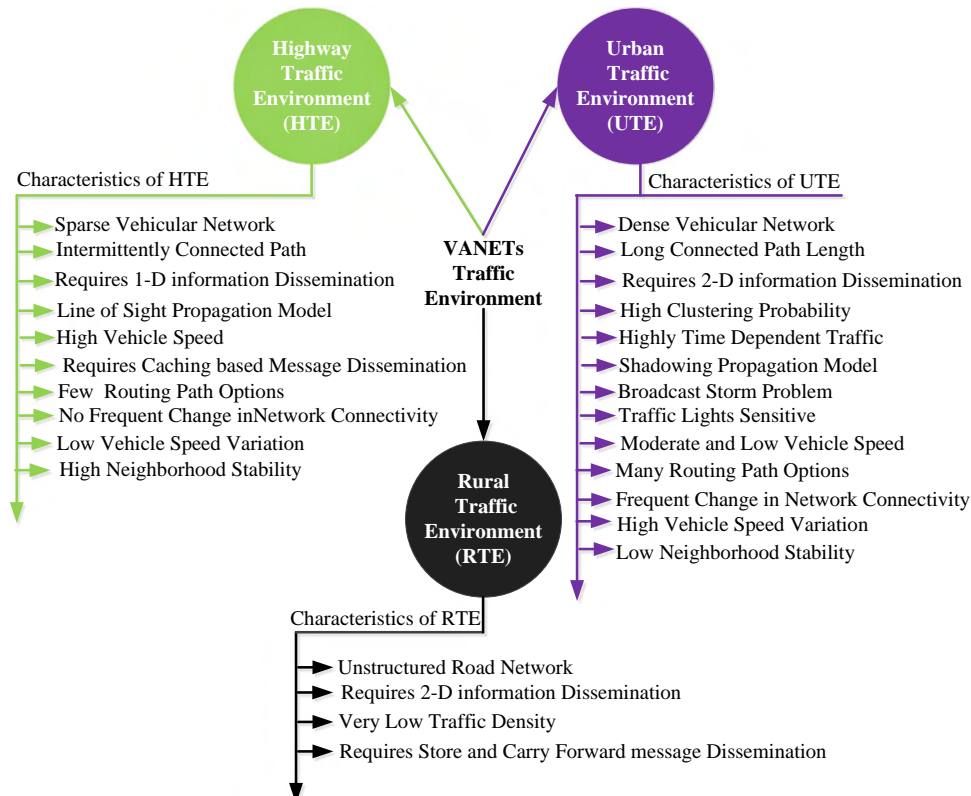


Fig. 3. Characteristics of the three traffic environments in VANETs.

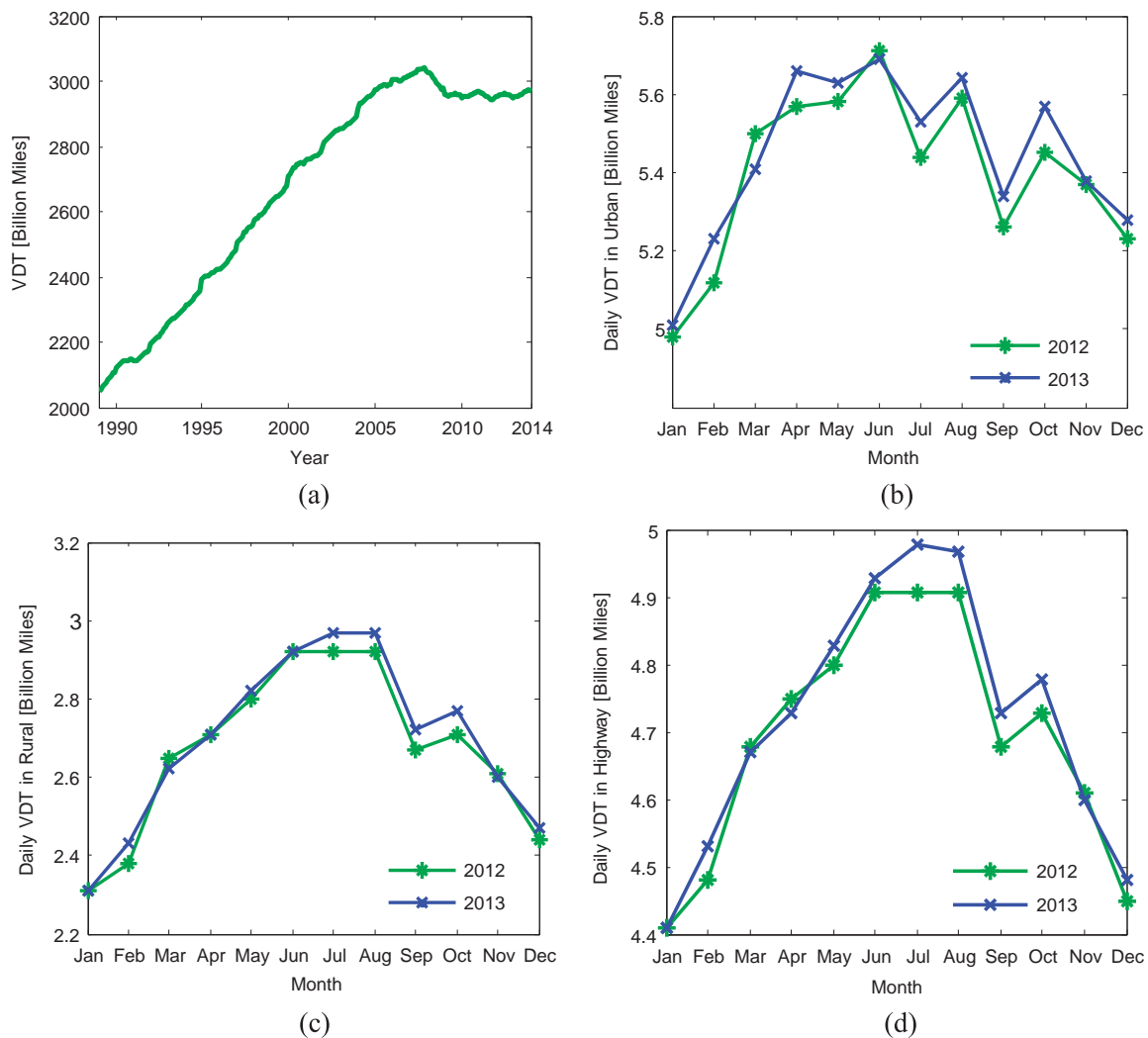


Fig. 4. Vehicle distance travelled (VDT) (a) Year wise distribution of VDT, (b) Month wise distribution of daily VDT in urban traffic environment, (c) Month wise distribution of daily VDT in rural traffic environments, (d) Month wise distribution of daily VDT in highway traffic environment.

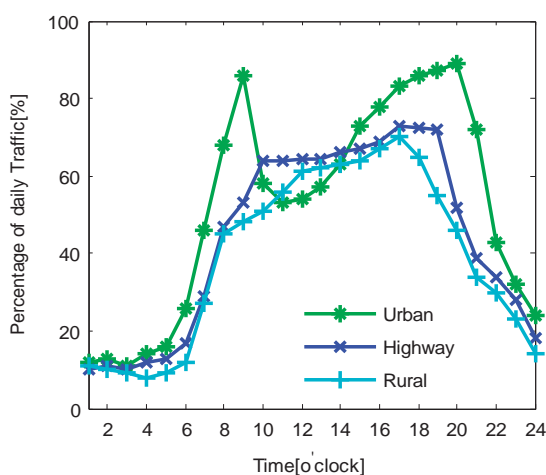


Fig. 5. Traffic volume distribution in 24 h of a day.

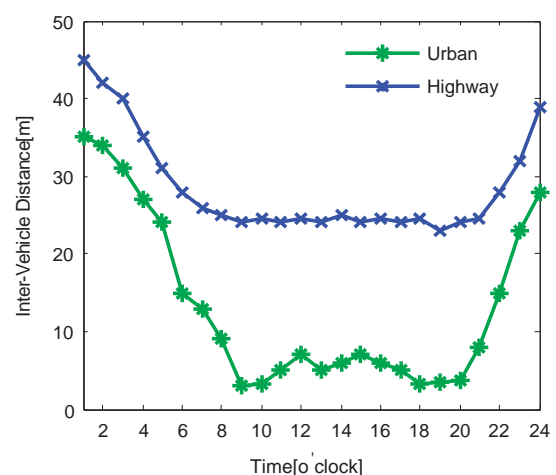


Fig. 6. Inter-Vehicle Distance distribution in 24 h of a day.

The real traffic data depicted in Fig. 5 shows the comparison of traffic volume distribution in 24 h of a day among urban, highway, and rural traffic environments. All the traffic environments scenarios show high traffic volumes between 8:00 to 20:00. The urban traffic environment has a higher traffic volume increment rate that starts from

5 o'clock in the morning and continuously grows till 9 o'clock reaching up to approximately 90%. After some drops from 10 o'clock to 12 o'clock, the urban traffic volume again increases in evening hours and reaches up to 90% at 20 o'clock. The traffic volume distribution of highway and rural traffic environments follows a similar pattern.

However, the traffic volume in the highway traffic environment is higher than that in the rural traffic environment. In Fig. 6 real traffic data on IVD for urban and highway traffic environments has been shown. It can be clearly observed that the urban traffic environment has smaller IVD as compared to the highway traffic environment. Additionally, the pattern of IVD is approximately similar for both urban and highway traffic environment. Nevertheless, the IVD of the urban traffic environment is quite smaller than the IVD of the highway traffic environment between 6:00–20:00.

2.3. Design challenges in incorporating physical parameters

The impact of physical parameters on vehicular traffic environments needs to be taken into account while designing the information dissemination technique owing to the dynamic behavior of traffic environments, which rely on physical parameters as is analyzed in the previous section. The physical parameters, namely, VDT, traffic volume, IVD, speed, lane occupancy, and traffic variability dynamically change. Therefore, optimizing these parameters and developing multi-metric information dissemination techniques based on location-centric forwarding is a significantly challenging task because of the number of physical parameters and different ranges of values of these parameters. Metaheuristic techniques can be utilized for parametric optimization, but conversion from multi-objective optimization to single-objective optimization and developing deterministic metaheuristic techniques are challenging problems in the use of these techniques for information dissemination in VANETs [86].

2.4. Impact of weather condition on traffic environment

Weather condition have a significant impact on traffic environments. Weather conditions are broadly categorized into three types, namely rain (or snow or flood), storm, and fog (or smog). The real traffic data has been used to analyze the quantitative impact of weather conditions on freeway traffic flow in terms of average speed, volume and capacity.

In Fig. 7(a), the impact of the weather condition on freeway traffic speed is shown. The figure reveals that because of normal rain (Rain-N), freeway traffic speed reduces in the range 4–14% whereas 4–16% reduction is recorded in the case of heavy rain (Rain-H). In a normal snow (Snow-N) situation, freeway traffic speed reduces in the same range as in Rain-N situation whereas 5–40% reduction is recorded in a heavy snow (Snow-H) situation. The freeway traffic speed reduction range recorded in fog is 10–12%. The Fig. 7(b) shows the impact of the weather condition on traffic volume. It can be observed that because of Rain-N, the traffic volume reduces in the range 6–10% whereas a 15% reduction in volume has been recorded due to Rain-H. The traffic volume reduction due to Snow-N is the same as that due to Rain-N whereas Snow-H causes 30–45% volume reduction. The traffic volume reduction range due to fog is 4–8%. Traffic capacity reduction due to different weather conditions is depicted in Fig. 7(c). It shows that the traffic capacity reduction range due to Rain-N is 4–11% whereas it is 10–30% due to Rain-H. Snow-N causes the same reduction as in Rain-N whereas the recorded traffic capacity reduction range due to Snow-H is 11–28%. The recorded traffic capacity reduction range due to fog is 12–14%. The above analysis, showing the impact of weather condition on traffic environment, has been pictorially summarized in Fig. 8. In the pictorial representation, the impact has been broadly categorized into three groups: rain (or snow or Flood), storm, and fog (or smog).

2.5. Design challenges in incorporating weather condition

Weather conditions have a significant impact on vehicular traffic environments as analyzed using real traffic data in the previous section. Therefore, the performance of information dissemination techniques is also affected by weather conditions, which determines the number of

parameters of vehicular traffic environment such as road capacity, speed, delay, accidental risk, availability of road network, density, driving effort, etc. Our observation proves that weather conditions need to be considered while designing information dissemination techniques based on location service for VANETs. Hybrid information dissemination techniques are required that can change the behavior of the protocol according to the dynamic changes in weather conditions. Designing hybrid location-centric information dissemination techniques for VANETs is a challenging task, considering the protocol complexity and the scalability requirement owing to the distributed network environment [87].

3. location-centric data dissemination

Unix-Unix Copy Mapping (UUCP-MAP) was the first project that introduced geocasting in Internet research [28]. UUCP-MAP was attempted to relate IP-addresses with geographic locations by maintaining a database to store geographic locations of Internet hosts. Later in similar projects, Farrell et al. [29] and Davis et al. [30] also tried to relate the Domain Name System (DNS) names to geographic locations. In these projects, geographic longitude and latitude information were incorporated with the DNS by extending the DNS data structure. The data structure extension enabled the systems to recognize data flows by their geographical region but directing data flows to a geographical region, was not possible. Routing based on geographic locations was first introduced by Finn in [31] with Cartesian routing. The address used in Cartesian routing has two parts. The first part represents longitude and latitude based locations and the second part represents a unique name. In Cartesian routing, a packet is always forwarded to the neighboring node that is closest to the destination node. In case a closer neighboring vehicle is unavailable, the search space of the neighboring vehicle is enlarged by n-hop distance. GPS-based addressing and routing were re-investigated by Imielinski [1]. He had presented a number of protocols and addressing schemes for the integration of the GPS into the Internet protocol to facilitate the formation of a number of location-dependent services.

Recent development of Geocast Routing Protocols (GRPs) in VANETs are reviewed here. The GRPs in VANETs can be broadly categorized into two categories: urban and highway protocols. Applicability in the specific traffic environment is the basis of the categorization. The categorization of GRPs considered in the work is shown in Fig. 9.

3.1. Advances in urban traffic environment

Recently, the urban traffic environment has gained the attention of researchers of VANETs [32–39]. This environment has been attributed with a high density of vehicles, limited vehicle speeds, high variance in speeds, better availability of forwarding options and high probability of shadowing. These characteristics distinguish the urban traffic environment from the highway traffic environment. Some recently proposed geocast routing protocols for the urban traffic environment are described below.

In some ITS application such as warning system, the disseminated information needs to be live for a specific duration of time in the geographical region. The duration of message life time varies depending on types of warning. In T-TSG, a time stable geocast routing algorithm that considers the traffic lights status has been proposed for the urban traffic environment. One possible situation for the use of T-TSG in urban traffic environment is explained in Fig. 10. T-TSG has four conceptual considerations as follows [40].

- **Geocast Region (GR) identification:** T-TSG recognizes GR considering the location of an incident, direction of vehicles involved in the incident, and road architecture of the incident region.
- **Traffic light based forwarding vehicle selection:** T-TSG always selects the Next Hop Vehicle (NHV) from the lane having the green

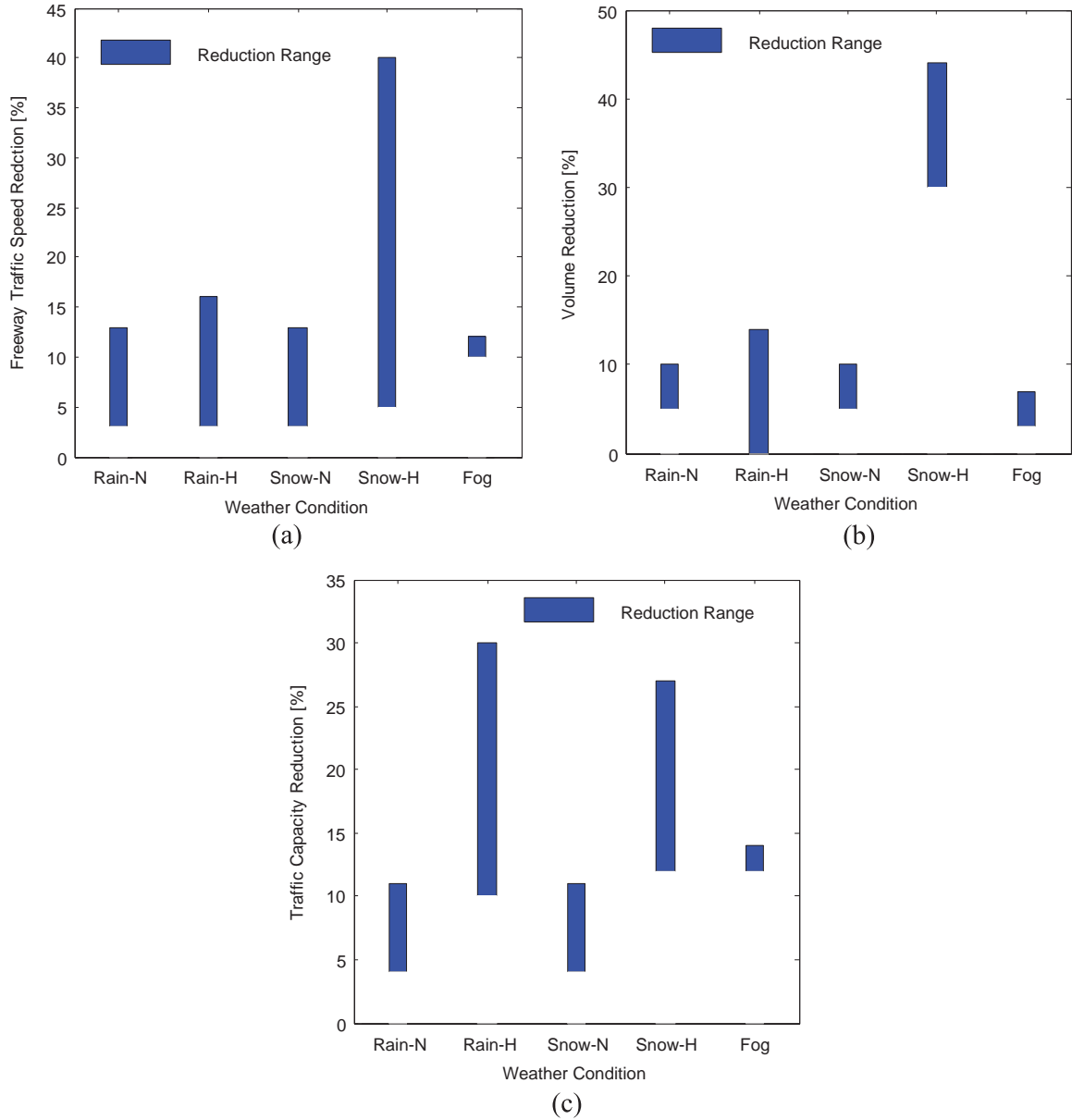


Fig. 7. Impact of weather condition on (a) Freeway traffic speed, (b) Volume and (c) Traffic capacity.

light ON.

- **Geocast Message Stable Region (GMSR) and Stable Vehicle Region (SVR)** : T-TSG also recognizes the lane where a geocast message needs to be stable for a specific time duration and the group of vehicles responsible for life time management of the geocast message.
- **T-TSG routing algorithm**: T-TSG is a three phase complete geocast routing algorithm. The phases of T-TSG are Forwarding, Disseminating and Re-Live (FDRL).

Vehicular trajectories are exploited to present coverage-oriented geocasting in [41]. Authors have considered network as a set N of vehicles. A road segment between two junctions j_1 and j_2 is represented by $RS_{1,2}$ and trajectory of i^{th} vehicle denoted by TR_i is considered as set of road segments. A packet is represented by p and source vehicle of a packet p is denoted by $SV(p)$. The destination geocast region of packet p is denoted by $DGR(p)$ and is a collection of clustered road segments. Any packet delivery of packet p is called successfully if and only if the carrier vehicle $v \in N$ of packet p passes through a road segment

$RS_{i,j} \in DGR(p)$.

A distributed algorithm for geocast routing is developed. The algorithm is based on *coverage graph* G_c . Each vehicle maintains its own G_c . The coverage graph of i^{th} vehicle $G_c(i)$ is expressed as

$$G_c(i) = \langle V_c(i), E_c(i) \rangle \quad (1)$$

where $V_c(i)$ represents a set of vehicles and $E_c(i)$ denotes a set of edges of the coverage graph. The vertex set $V_c(i)$ is a collection of road segments RS_x^v defined as

$$RS_x^v \in V_c(i), \quad 1 \leq x \leq m, \quad \forall \quad TR_v \in TS_i \quad (2)$$

where TS_i represents the set of trajectories known by the i^{th} vehicle and $TS_v = \{RS_1^v, RS_2^v, RS_3^v, \dots, RS_m^v\}$ is the trajectory of v^{th} the vehicle. The edge set $E_c(i)$ is a collection of edges drawn between two road segments of either the same trajectory or two different trajectories.

The *coverage graph* is utilized to calculate the *coverage capability*. The coverage capability of a vehicle v for any destination geocast region DGR is denoted by $\tau(v, DGR)$ and calculated as

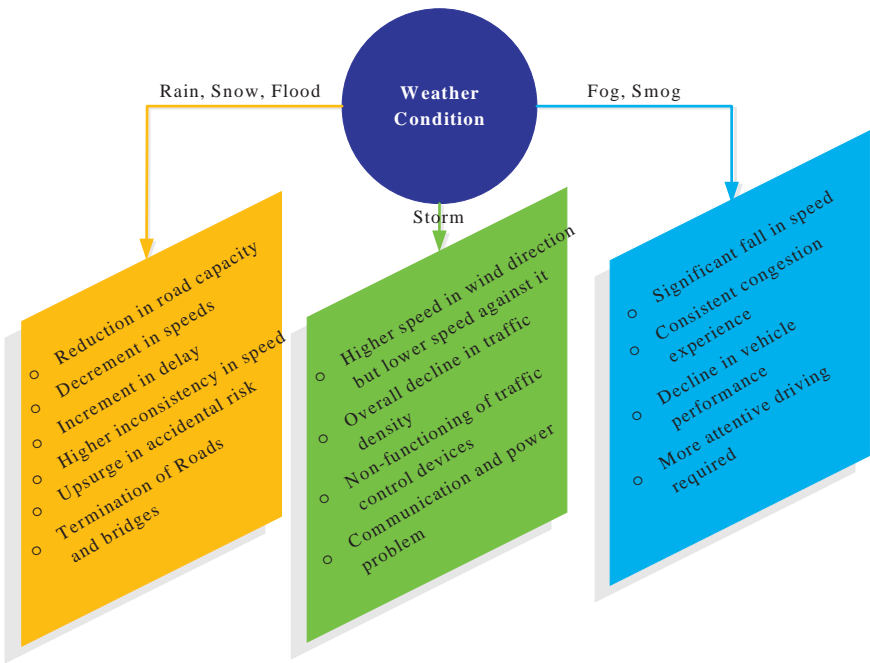


Fig. 8. Categorization of impact of weather conditions on traffic environments.

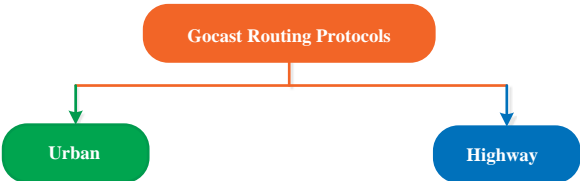


Fig. 9. Two classification of geocast routing protocols in VANETs.

$$\tau(v, DGR)=\max \{MV(l), \rho(v, DGR)\} \tag{3}$$

where, $MV(l)$ represents the calculated matrix value of path l and $\rho(v, DGR)$ denotes a set of all routing paths reaching to DGR from vehicle v . The calculation of the coverage graph based on vehicle trajectories is shown in Figs. 11 and 12.

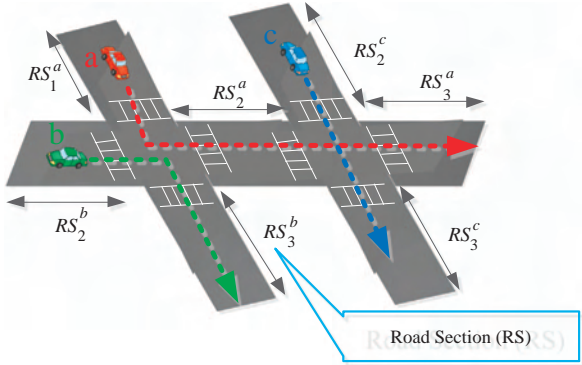


Fig. 11. Trajectories of vehicles a, b and c.

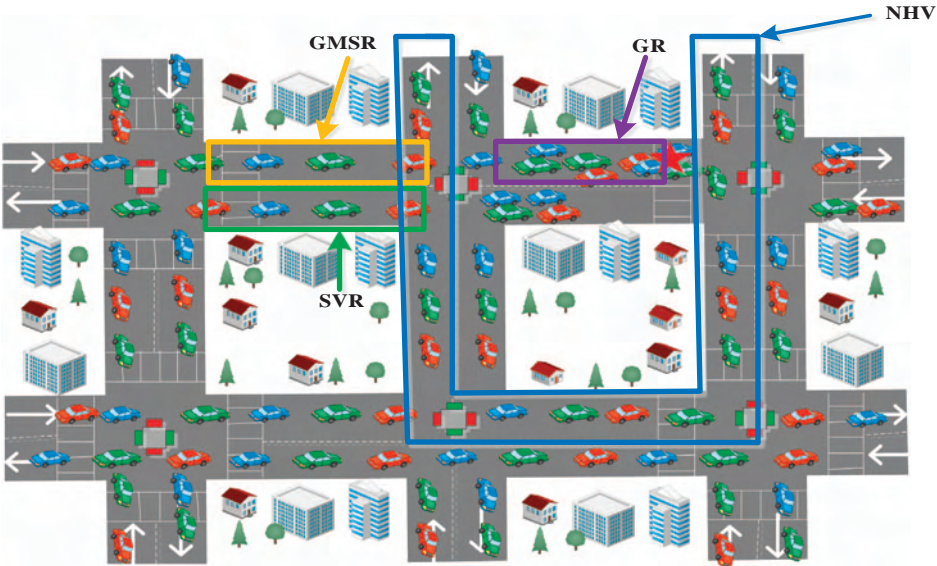


Fig. 10. A glance of applicability of T-TSG in urban traffic environment.

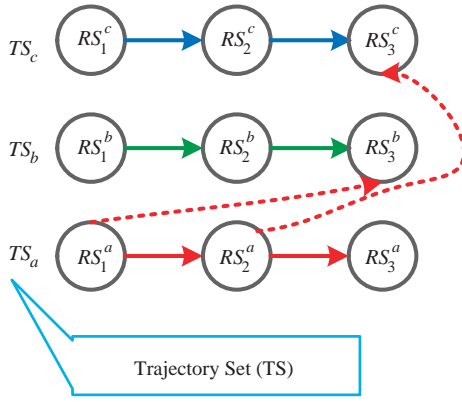


Fig. 12. Coverage graph of vehicle a .

VLDA [42] computes the vehicle density and the traffic load as Network Information Collection Packet (NICP) in a distributed manner. The NICP is further used to calculate the weight for each adjacent road section by the junction vehicle. The weight of a road section W_r is expressed as

$$W_r = f_1 (1 - D) + f_2 \left(\frac{V_d}{1 + V_d'} \right) - f_3 t \quad (4)$$

where f_1 , f_2 and f_3 represent weighing parameters, D denotes closeness of the candidate junction to the destination vehicle, V_d symbolizes vehicle density on road section, V_d' indicates vehicle density on current vehicle's transmission range and t denotes the time required to transmit the total traffic load.

VLDA also improves the accuracy of routing table information by real-time distance calculation between the current forwarder and the NHV. It also presents two algorithms for enhancing HELLO mechanism and for packet forwarding.

Shortest path-based Traffic light Aware Routing (STAR) has been suggested in [43] to reduce the effect of network partition in routing by considering traffic light behavior. Authors presented two forwarding schemes, namely STAR and green light forwarding (GLF). STAR always tries to forward a packet through a road segment having red light ON and connected links up to the next junction, and whereas GLF always forwards a packet through a road segment having green light ON (cf. Fig. 13). The data delivery ratio of STAR and GLF has been studied using statistical methods and it has been proved that the delivery ratio

of STAR is better than that of GLF.

The probability of having a path of connected links between two junctions with red light ON is also derived. The road segments between two junctions having red light ON is called red light segment (RLS). The probability of connected red light segment P_{conn}^{RLS} is expressed as

$$P_{conn}^{RLS} = 1 - \sum_{j=1}^{M-L-1} (P_i^{Mul} \times P_{disconn}^{adj}) \quad (5)$$

where M represents the maximum number of sections possible on a RLS, L represents the number of possible sections in a transmission range of vehicle, P_i^{Mul} denotes the probability that a car of i th sections can reach the last section of RLS using multihop forwarding, $P_{disconn}^{adj}$ represents the probability that two consecutive vehicles are disconnected.

3.2. Comparative study of urban protocols

Comparative study of recently developed protocols for the urban traffic environment has been performed. The comparison is made based on some special characteristics of urban environment such as interference, high vehicle density, lower speed, junctions, etc., as well as some general routing metrics of VANETs. The comparative assessment provides the main characteristics of each protocol considered in our study. The assessment also reveals that different protocols have different routing goals and hence the protocols have been evaluated differently. The comparative evaluation is summarized in Table 1.

3.3. Advances in highway traffic environment

The highway traffic environment is characterized by sparse vehicular networks, frequent network fragmentation, short link life time, high speeds, multi-lane roads, very large road segments, well-defined exits and on-ramps, quasi one-dimensional vehicle movements etc. These characteristics of highways pose challenges, particularly in routing [44]. Some recently proposed routing protocols suitable for geocasting in the highway traffic environment are explored below.

The constraints of information dissemination imposed by the highway traffic environment are efficiently addressed in [45]. FBPR divided the task of routing into various well-defined modules to achieve the desired performance. The routing modules are radio channel, beacon rate, location prediction, next hop selection, location service, and data dissemination. The path loss model for the highway traffic environment presented in [46] is used for communication. The path loss for propagation distance, PT_{loss}^d is expressed as

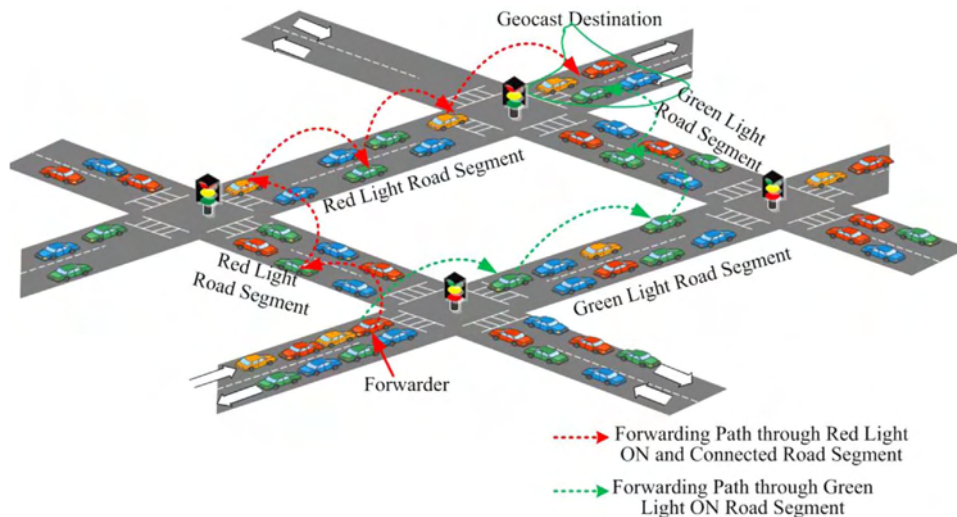
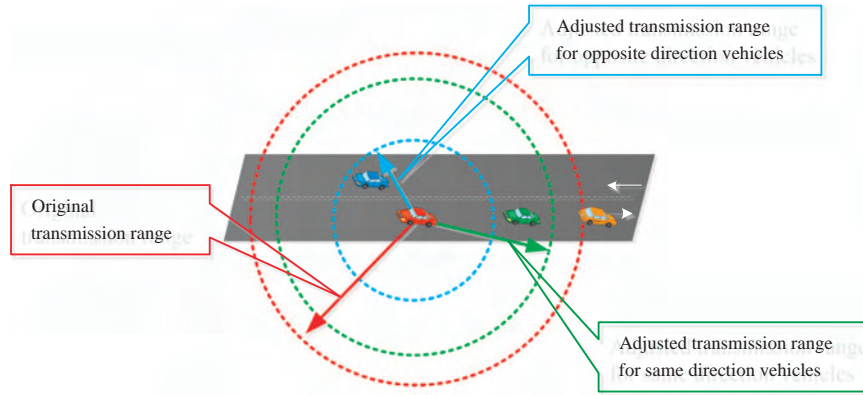
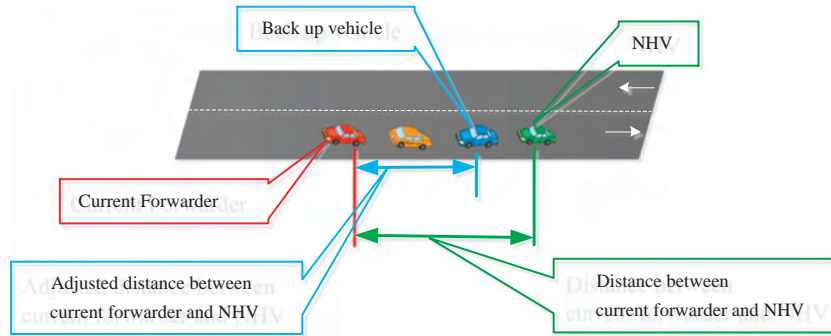


Fig. 13. Forwarding through red light ON with connected road segment and green light ON road segment.

Table 1

Comparative assessment table for protocols considering urban environment.

Protocols				
Characteristics	T-TSG	CAGR	VLDA	STAR
Interference	Considered in simulation	Not considered	Not considered	Considered in simulation
Vehicle Density	High	Average	Low	Average
Junction	Considered	Considered	Not considered	Considered
Forwarding Technique	NHV based	Coverage based	Junction based	Intersection based
Location Information	Through GPS	Through GPS	Through GPS	Through GPS
Simulator	ns-2	MATLAB	ns-2	ns-2
Digital Map Requirement	Yes	Yes	Yes	Yes
Scalability	High	Medium	High	High
Complexity	Low	Low	Medium	Low
Recovery Technique	Link re-calculation	No recovery policy	Time stamp based recovery	Carry-and-forward based recovery
Scenario awareness	Yes	Yes	Yes	Yes
Path Technique	Sender to stable region and geocast full path	Single link	Junction-to Junction full path	Intersection of transmission range based complete path
Infrastructure Requirement	Not needed	Not needed	Not needed	Not need
Neighbor Direction	Opposite	Assumed same	Both (same and opposite)	Both (same and opposite)
Beacon Packet Requirement	Yes	Yes	Yes	Yes
Caching Capability	Available	Not available	Not available	Available
Obstacle Knowledge	Not aware	Not aware	Aware	Aware
Path Selection Metric	Distance	Coverage	Distance	Distance
Neighbor lifetime knowledge	On-demand beacon	Fixed interval beacon	Dynamic interval beacon	Fixed interval beacon
Drawbacks	No density awareness	Implicit link assumption by coverage	Longer distance between junction may degrade performance	Shortest path reliability is not always true

**Fig. 14.** Transmission range adjustment for same-direction and opposite-direction vehicles.**Fig. 15.** Back up vehicle selection using adjusted distance between current forwarder and NHV.

$$PT_{loss}^d = PT_{loss}^{d_0} + 10n \log_{10} \left(\frac{d}{d_0} \right) + Y_\sigma + \gamma PT_{loss}^c \quad (6)$$

where $PT_{loss}^{d_0}$ represents the path loss at reference distance d_0 , n denotes the path loss exponent, Y_σ symbolizes a normally distributed random variable with zero mean and standard deviation σ , relative vehicle direction is represented by γ , and PT_{loss}^c is some constant correction term. FBPR uses a dynamic beacon rate based on vehicle density. A

Location Prediction (LP) algorithm is used to verify and make corrections on the vehicle's stale location entry in the routing table just before any transmission of a packet. The NHV is selected using a most forward within adjusted radius (MFWAR). The MFWAR adjusts the transmission range of neighboring vehicles according to moving direction (cf. Fig. 14). A location service is used to find the destination location whenever a data packet arrives without destination location information. A redundancy strategy is used for re-dissemination of



Fig. 16. Information waits in vehicles moving towards east.

discovery packets if the discovery packet does not reach the intended relay vehicles. This re-dissemination is carried out back up vehicles. A back up vehicle is selected by adjusting the distance between the current forwarder and NHV (cf. Fig. 15). An implicit acknowledgement is used in FPBR. Whenever a sender vehicle hears a packet forwarded by it, then the vehicle implicitly assumes it as an acknowledgement for the packet.

The speed of information propagation in a highway is analytically studied in [47]. In this analysis, vehicles on a two way highway follow Poisson distribution. Let ρ_{east} and ρ_{west} represents the vehicle density on roads going east and west respectively and R denotes the transmission range. The main result of information propagation speed analysis states that coincidence of $(\rho_{east} \times R)$ and $(\rho_{west} \times R)$ on the curve $y = xe^{-x}$ results in a phase transition as

$$\{\rho_{east} \times R \times e^{-(\rho_{east} \times R)}\} = \{\rho_{west} \times R \times e^{-(\rho_{west} \times R)}\} \quad (7)$$

The threshold value of propagation speed is obtained as $R = 1 \text{ km}$. The information propagation speed is limited to vehicle speed for $R < 1 \text{ km}$ and faster than vehicle speed for $R > 1 \text{ km}$. This is because the multi-hop communication takes place without the use of caching in the case of $R < 1 \text{ km}$ and the approach of utilizing vehicle speed with caching is adopted in the case of $R > 1 \text{ km}$. The average speed of information propagation S_p is expressed as

$$S_p = \lim_{t \rightarrow \infty} \frac{E[d(t)]}{t} \quad (8)$$

where $E[d(t)]$ represents the expected distance travelled by information during time t . The three theorems related to the threshold of phase transition of information propagation, the distribution of waiting time of information packets (cf. Fig. 16) and total propagation distance travelled by information packets (cf. Fig. 17) have been given and analytically proved.

VANETs have been categorized into urban and highway VANETS and a pseudo-code based study of existing position-based routing protocols has been reported in [48]. The difference between urban and highway traffic environments in terms of traffic scenario, mobility pattern, mobility properties, etc. is briefly discussed, and is helpful in precisely classifying position-based routing protocols in urban and highway environments. Various strategies of position-based routing such as path selection, forwarding, and recovery mode are closely investigated and performance of each strategy is evaluated in terms of various matrices such as overhead, availability, resilience, and latency. Several position-based routing protocols with their pseudo-code are explored and a comparative evolution of these protocols in urban and highway traffic environments is also presented.

A geocast routing protocol named as Mobicast for non-emergency

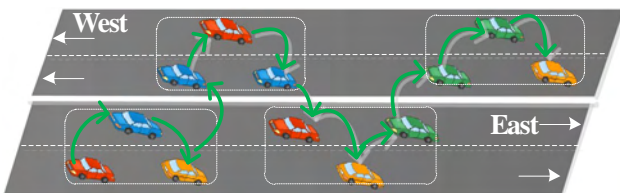


Fig. 17. Information travel path including east and west direction vehicles.

comfort applications in highway traffic environments is suggested in [49]. Mobicast uses ZOR at time t denoted as ZOR_t and zone of forwarding at each time $(t + i)$ represented as ZOF_{t+i} . Each Mobicast forwarder determines an elliptical region with an application dependent major axis and a lane width dependent minor axis. This elliptical region is called ZOR (cf. Fig. 18). Each vehicle of ZOR must receive the Mobicast Message (MM) within a pre-specified delay. Each Mobicast forwarder also determines two ZOF, one towards front and other towards back side. Each vehicle of ZOF is responsible for carrying and forwarding to MM.

The three phases of Mobicast, namely ZOR_t creation, ZOF_{t+i} estimation and message dissemination are used to deliver message before time $(t + \alpha)$ to all vehicles of ZOR_t . ZOR_t of a vehicle $V_1(a, b)$ w.r.t. another vehicle $V_2(c, d)$ is expressed as

$$ZOR_t\{(a, b), (c, d)\} = \frac{(a - c)^2}{x^2} + \frac{(b - d)^2}{y^2} - 1 = 0 \quad (9)$$

where x and y represent major and minor axes, respectively. The ZOF_{t+i} of vehicle $V_1(a, b)$ w.r.t. front vehicle $V_f(c, d)$ and rear vehicle $V_r(e, f)$ is calculated using Eq. (9) by adopting different major axes for front and rear vehicles. After calculating ZOR_t and ZOF_{t+i} the message is disseminated using either multi-hop forwarding or Mobicast Carry-and-Forward (MCF) techniques.

3.4. Comparative study of highway protocols

A comparative study of recently developed protocols is carried out considering the highway traffic environment. The comparison is made based on some especial characteristics of the highway environment such as forwarding space, lane consideration, IVD, etc. as well as some general routing metrics of VANETs. The comparative assessment provides the main characteristics of each protocol considered in our study. The assessment also reveals that different protocols have different routing goals and hence the protocols have been evaluated differently. The comparative evaluation is shown in Table 2.

4. Open research problems in geocast routing

Recent years have witnessed intense research activities in geocast routing. Sustained and sincere efforts of researchers have made geocast routing one of the finest routing techniques used in various ITS applications. Nevertheless, some unsolved research problems in geocast routing remain that are related to either the drawbacks of current works or to untouched aspects. These issues are listed below.

• Design of efficient caching technique

The effective utilization of vehicle speed for packet delivery, especially in intermittently connected networks is possible only with the availability of efficient caching techniques [50,51]. Although caching technique reduces network load and packet loss, they increase end-to-end delay in packet delivery. Therefore, we need an efficient caching technique to effectively maximize the advantages of caching and minimize disadvantages in geocast routing [52].

In Fig. 19, an example of information dissemination without using efficient caching is depicted. To successfully forward the accident message from the source region to the destination geocast region, the presence of at least one forwarding vehicle in all the $1 - n$ transmission circles is a must. The unavailability of a forwarder in any of the transmission circles would result in the loss of information. The consideration of a forwarder availability in each transmission circle is an idealistic assumption, considering the highly dynamic on-road traffic environment in realistic vehicular environments [53]. Therefore, the design of efficient caching is indeed a promising research theme in geocast routing in VANETs.

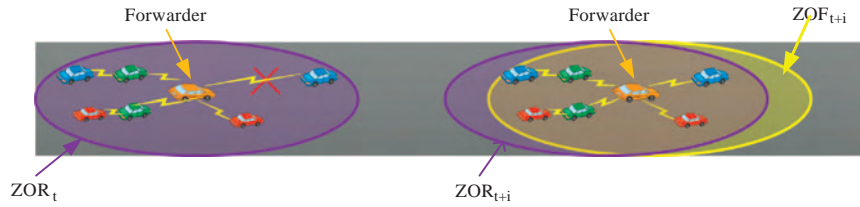


Fig. 18. Elliptical representation of ZOR_t and ZOF_{t+i} .

Table 2

Comparative assessment table for protocols considering highway environment.

Protocols				
Characteristics	FPBR	IPSA	AGR	MR
Forwarding space	Two direction	Single direction	Single direction	Two direction
Lane consideration	Yes, four lanes	No, single lane	Yes, six lanes	Yes, four lanes
Inter vehicle distance	Stable	Stable	Not considered	Not considered
Speed	High	low	High	High
Forwarding Technique	NHV based	Cluster based	NHV based	Carry-and-forward
Location Information	Through GPS	Through GPS	Self-localization	Through GPS
Simulator	OPNET	Mapel and ONE	NS2	NCTUns
Digital Map Requirement	Yes	Yes	yes	Yes
Scalability	High	High	low	High
Complexity	Medium	Low		Low
Recovery Technique	Back node based recovery	Not required	Angle based	Not require
Scenario awareness	Yes	Yes	No	Yes
Path Technique	One hop technique	Complete path in each cluster	Complete path in Junction	One hop technique
Infrastructure Requirement	Not needed	used	Not needed	used
Neighbor Direction	Both (same and opposite)	Opposite	Assumed same	Assumed same
Beacon Packet Requirement	Yes	No	yes	Yes
Caching Capability	Not available	Available	Not available	Available
Obstacle Knowledge	Not aware	aware	Not aware	Not aware
Path Selection Metric	Distance & link quality	Distance	Angle and distance	Distance
Neighbor lifetime knowledge	Dynamic interval beacon	Fixed interval beacon	Dynamic beaconing	Fixed interval beacon
Drawbacks	Module dependency in case of any module failure	It is only an analysis and cannot be used as facts	Low scalability due to complex modelling	Restricted for comfort application

• Detection of one-hop link disconnection

VANETs are highly mobile networks compared to other kinds of ad hoc networks [54]. High-speed mobility of vehicles results in frequent network topology changes in VANETs. Frequent topology changes are the prime cause of the high one-hop link disconnection rate in VANETs [55]. An increased packet loss rate has been reported in routing in VANETs due to the frequent loss of one-hop connectivity in transmission [56]. Therefore, we need an effective one-hop link disconnection detection technique that can be used in geocast routing.

In Fig. 20, the one-hop link disconnection problem is illustrated. Probable NHVs A, B, C and D are going to different destinations D_1 , D_2 , D_3 and D_4 respectively. In this scenario, D will be most appropriate NHV considering the fact that it will remain in the direction of the geocast region for a longer duration of time.

However, this determination is static because it includes only the future traveling distance towards the destination geocast region. A heuristic-based technique can be found in [53] for this purpose. Therefore, a need exists to include other traffic parameters in this determination for making it more suitable and identifying future one-hop disconnection in advance and take pre-caution accordingly.

• Coordination between Most Forward within Radius (MFR) and link quality

MFR is one of the most investigated choices for researchers in forwarding [57]. MFR results in the lowest end-to-end delay especially in the absence of obstacles and stationary network environments [58]. Radio signal obstacles are high in numbers in the urban vehicular traffic environment [59]. Therefore, the quality of link also becomes an

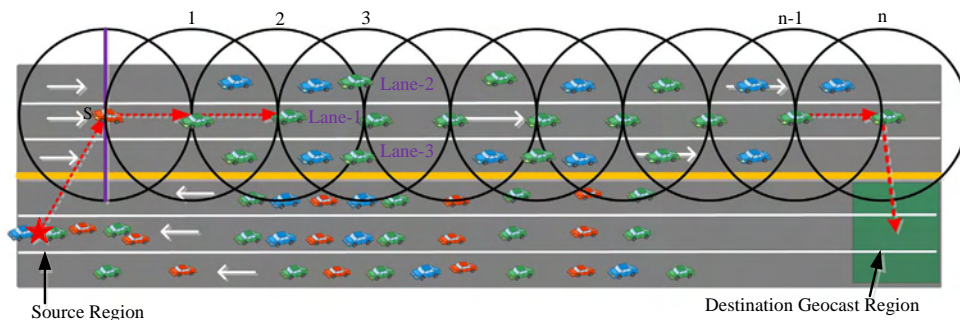


Fig. 19. Illustration of problem of geocasting without using caching.

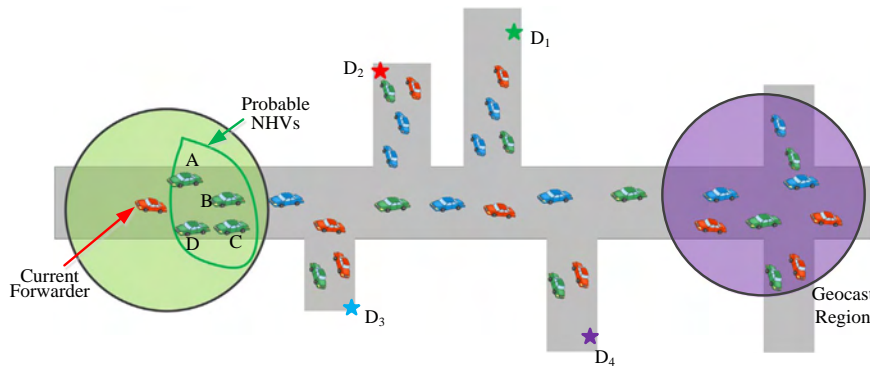


Fig. 20. An example of problem of one-hop link disconnection.

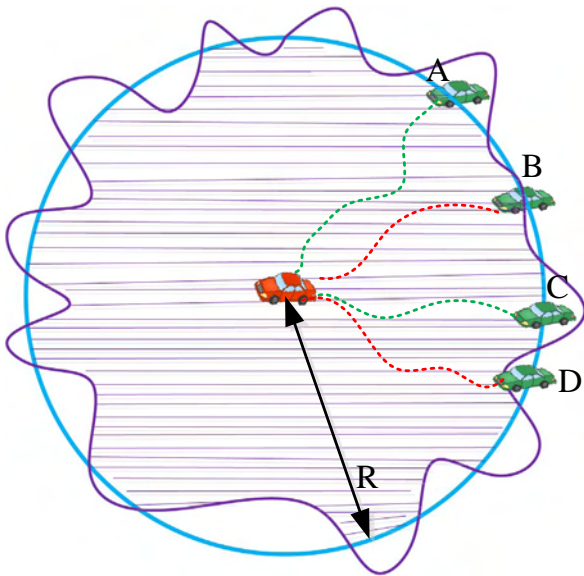


Fig. 21. MFR and link quality coordination problem.

important issue in routing in VANETs. MFR and link quality do need to be investigated together for better geocast routing performance in the urban traffic environment [60].

In Fig. 21, the requirement of coordination between MFR and link quality is illustrated. There are four vehicles A, B, C and D which are at the border of a forwarder vehicle. Due to the shadow fading effect, signal propagation in a wireless medium does not remain the same in all directions. Therefore, the communication range of any forwarder vehicles becomes non-circular and the signal fluctuates at the border region. Due to this fluctuation, communication links of vehicles A, and C are better as compared to the links of vehicles B and D. Therefore, the coordination between MFR and link quality will improve the NHV selection technique in multi-hop geocast routing in VANET.

• Guaranteed delivery in sparse traffic networks

Highway vehicular traffic environment is considered sparsely connected in VANETs [61]. Packet delivery from source to destination in the highway traffic environment is unreliable due to the sparsely connected nature of the networks. A smart packet delivery technique that guarantees delivery through acknowledgement is the urgent need of the hour in geocast routing, especially in the highway traffic environment. In vehicular communication through geocast routing using three functional modules, namely beaconing, multi-hop forwarding and geo-location discovery packet delivery is not acknowledged and this results in doubtful delivery of packets [62]. For intermittently

connected environments, such as in highway vehicular traffic, the problem of doubtful delivery becomes more serious [63]. To reduce network load in highly dynamic vehicular communication, acknowledgement is not preferred in geocast routing, but some kind of mechanism is indeed required for ownership transfer of a packet that will guarantee end-to-end delivery in geocast routing.

In Fig. 22, the problem of guaranteed delivery in disconnected traffic environment has been illustrated. From the source region to the destination geocast region, there are some transmission range circles such as 9, 10 and 11. Because of this, the ownership transferring message from transmission circle 8 guarantees message delivery to transmission circle 12. This kind of delivery is possible with the use of a caching technique as the vehicle of transmission circle 8 which will reach circle 12 and deliver the message.

• Optimized next hop vehicle and least displaced vehicle selection

NHV and Least Displaced Vehicle (LDV) selection have become critical issues in routing owing to its usage in almost every multi-hop routing protocol in VANETs [64–66]. The performance of multi-hop routing is completely dependent on the reliability of NHV and/or LDV selection technique. Therefore, we need effective NHV and LDV selection methods that can be used in geocast routing during multi-hop forwarding.

In Fig. 23, the current forwarder vehicle F has a number of choices for selecting NHV considering a realistic urban scenario. For selecting an appropriate NHV, the current forwarder evaluates each vehicle in terms of various geocast routing metrics. Due to the high vehicle density and large number of routing metrics, the computational complexity of the NHV selection process is high. Therefore, the optimization of NHV selection is one of the crucial future research issues in geocast routing. Particle swarm optimization used in [67] could be considered as a better approach in this direction.

• Distributed location information verification

Location information security has been gaining momentum among researchers in VANETs owing to the increasing number of location information dependent ITS applications [68]. In geocast routing, each vehicle broadcasts its location information to all neighboring vehicles. The broadcasted location information is used for forwarding without verifying the correctness of location information. Therefore, location information verification cum security technique is required in geocast routing [69,70]. Scalability and distributed nature have become two important characteristics of any proposed technique in VANETs owing to the high density and mobility of vehicles.

In Fig. 24, all neighboring vehicles are broadcasting their location information to the current forwarder vehicle. The current forwarder vehicle needs to verify the broadcasted location information of

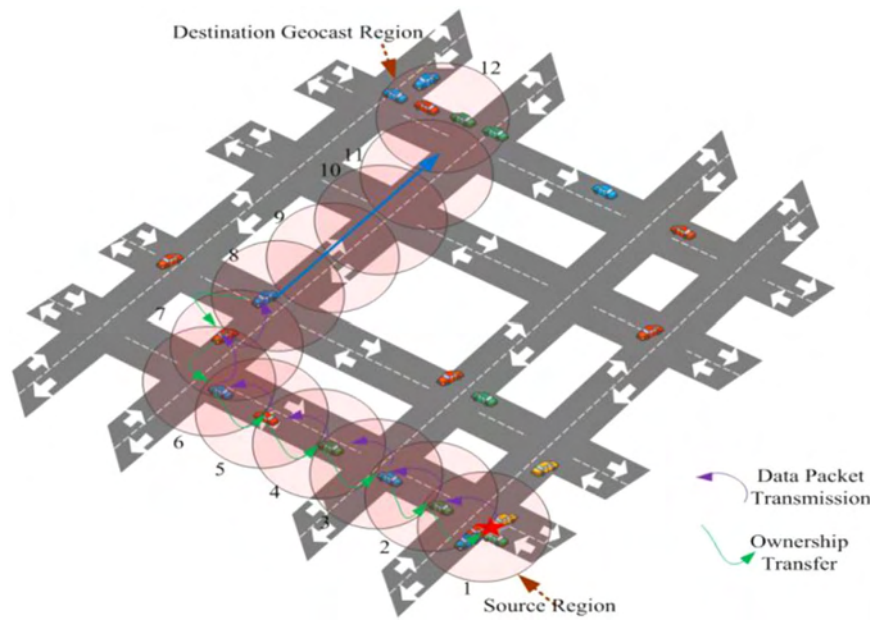


Fig. 22. Problem of guaranteed delivery in disconnected traffic environment.



Fig. 23. Optimized NHV selection problem in urban vehicular traffic environment.

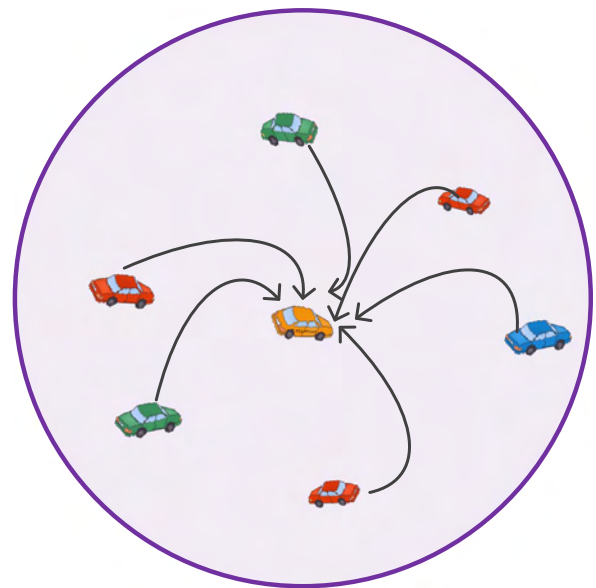


Fig. 24. Verification of location broadcasted by neighboring vehicles.

neighboring vehicles because the performance of any geocast routing protocol entirely depends on the correctness of location information. Any malicious vehicle can mislead current forwarding vehicle by broadcasting wrong location information and, thus, negatively impact the performance of geocast routing [71,72].

• Connectivity aware geocast routing

Scarcity of connectivity is a general phenomenon in vehicular traffic environment due to the highly dynamic network environment. Recently, connectivity in vehicular communication is attracting researchers [73] and thus, various connectivity area routing protocols have been suggested in the literature [74,75]. There are issues in connectivity area routing such as density-based connectivity estimation and rectangular area based junction selection, beaconing rate based connectivity estimation, impact of interference on connectivity [76–78], etc. that need to be addressed for the development of Connectivity

Aware Geocast Routing (CAGR) protocols.

In Fig. 25 two road sections have equal density but the road Section 1 is not connected whereas road Section 2 is connected. Therefore, density based connectivity estimation for geocasting is not appropriate for vehicular traffic environment. Other parameters such as IVD, traffic light situation etc. need to be considered for effective connectivity estimation for geocast routing.

• Transport layer designs for effective geocast routing

Transport protocol design or improving traditional transport protocols for vehicular communication is a new research theme in VANETs [79,80]. A number of ITS applications require stable and durable connection between source and destination. Characteristic study of path for Vehicular Transport Protocol (VTP) design has been performed in [81]. Internet access in vehicular traffic environment has been realized in [82] by suggesting a Mobility control Transport

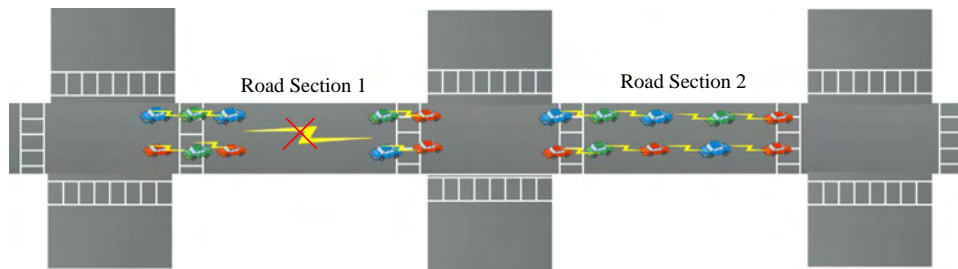


Fig. 25. Problem in density-based connectivity estimation in geocast routing.

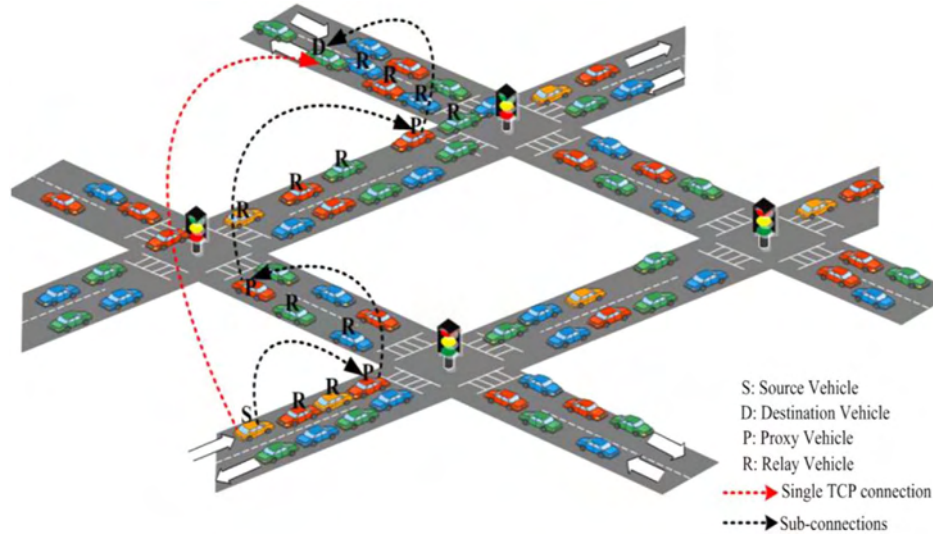


Fig. 26. Transforming a traditional TCP into VTCP.

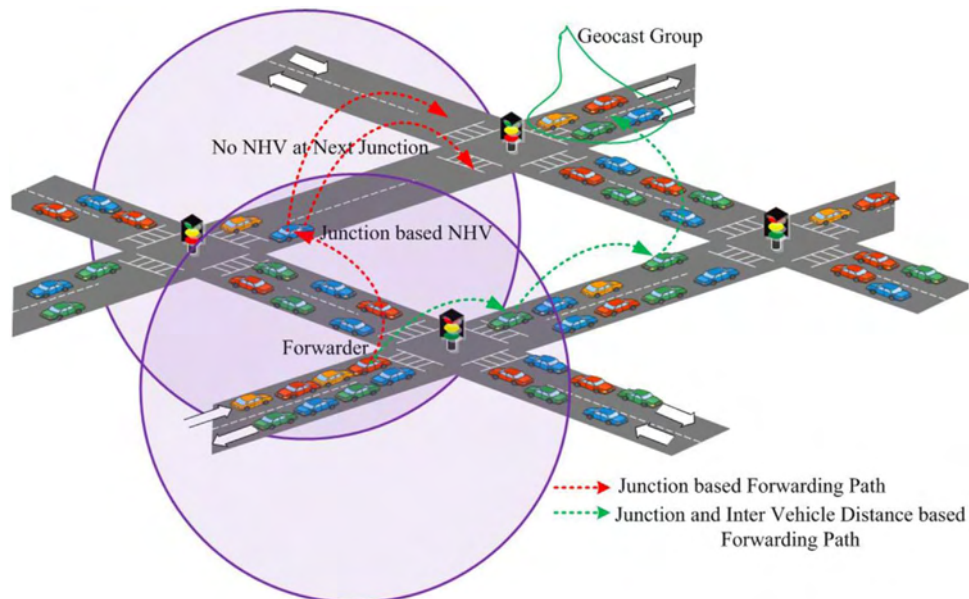


Fig. 27. Problem of pure junction-based forwarding.

Protocol (MTP) based on a proxy server. MTP divides each Transmission Control Protocol (TCP) connections into two sub-connections: Internet and proxy connection, and proxy and vehicles connections for reducing the impact of mobility in the performance of TCP. Various challenges [80] need to be addressed for developing an efficient VTP to effectively cooperate with geocast routing.

In Fig. 26, a conceptual approach for converting a traditional TCP connection into VTCP is illustrated by converting relay vehicles into temporary storage vehicles known as proxy vehicles. Although the approach looks promising considering highly dynamic network environments of vehicular communication, many issues need to be addressed that are related to the selection of appropriate proxy vehicles.

• Junction-based geocast routing

The Urban vehicular road network is highly congested and the existence of junctions every few kilometers could not be ruled out. Junction based message forwarding in vehicular traffic environments is attracting the researchers' attention [83–85]. Issues related to junction based routing such as effective next junction selection as well as, network load reduction by effective identification of group of junctions between source and destination need to be addressed to develop effective Junction based Geocast Routing (JGR) techniques. Angle-based greedy selection of junctions has been used in [83]. Multiple disjoint paths between source and destination going from intermediate junctions have been used in [84]. Road side gateways are used as servers in [85] for collecting real time on-road traffic information.

In Fig. 27, pure junction based forwarding fails because of not incorporating other traffic parameters such as IVD in NHV selection. Although junction-based forwarding is suitable for the urban traffic environment, a number of other traffic parameters need to be included for improving the performance of junction-based forwarding in geocast routing.

5. Conclusion

In this paper, vehicular traffic environments and location-centric data dissemination have been critically reviewed for identifying future design issues in location-centric data dissemination in VANETs. Real traffic data is utilized for analyzing the impact of physical parameters and weather conditions on traffic environments. State-of-the-art techniques of location-centric data dissemination have been qualitatively investigated considering functional and qualitative behavior of protocols, properties, and strengths and weaknesses for both urban and highway traffic environments. Traffic environment analysis helps in incorporating the behavior of physical parameters and weather conditions into data dissemination design. The classified study of location-centric data dissemination techniques assists in identifying appropriate techniques for specific ITS applications and suitable traffic environments as well as gives clear insight to researchers in understanding and differentiating various geocast routing protocols. The future research directions presented in the paper based on cutting edge research in the area will also lead to the development of new location-centric data dissemination techniques.

Conflict of interest

The authors declare no conflict of interest.

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References

- [1] O. Kaiwartya, A.H. Abdullah, Y. Cao, A. Altameem, M. Prasad, C.T. Lin, X. Liu, Internet of vehicles: motivation, layered architecture, network model, challenges, and future aspects, *IEEE Access* 4 (2016) 5356–5373.
- [2] Govt. of NCT of Delhi, An Approach to 12th Five Year Plan: Transport Department. http://www.delhi.gov.in/wps/connect/DoIT_Planning/planning/important+links/an+approach+to+12th+five+year+plan+%282012-17%29 (accessed 13 July 2014).
- [3] Y. Cao, T. Wang, O. Kaiwartya, G. Min, N. Ahmad, N. A.H. Abdullah, An EV charging management system concerning drivers' trip duration and mobility uncertainty, *IEEE Trans. Syst., Man, Cybern.: Syst.* 99 (2016) 1–12.
- [4] S.K. Dalya, O. Kaiwartya, A.H. Abdullah, Y. Cao, A.H. Hassan, S. Kumar, Location information verification using transferable belief model for geographic routing in VANETs, *IET Intell. Transp. Syst.* 11 (2016) 53–60.
- [5] V. Milanes, J. Villagra, J. Godoy, J. Simo, J. Perez, E. Onieva, An Intelligent V2I-based traffic management system, *IEEE Trans. Intell. Transp. Syst.* 13 (2012) 49–58.
- [6] A.H. Hassan, A.H. Abdullah, O. Kaiwartya, Y. Cao, S.K. Dalya, Multi-metric geographic routing for vehicular ad hoc networks, *Wirel. Netw.* (2017) 1–20. <http://dx.doi.org/10.1007/s11276-017-1502-5> online.
- [7] O.K. Tonguz, M. Boban, Multiplayer games over vehicular ad hoc networks: a new application, *Ad Hoc Netw.* 8 (2010) 531–543.
- [8] W. Chen, R.K. Guha, T.J. Kwon, J. Lee, Y.-Y. Hsu, A survey and challenges in routing and data dissemination in vehicular ad hoc networks, *Wirel. Commun. Mob. Comput.* 11 (2011) 787–795.
- [9] A. Khatri, S. Kumar, O. Kaiwartya, A.H. Abdullah, Green computing for wireless sensor networks: optimization and Huffman coding approach, *Peer-to-Peer Netw. Appl.* (2016) 1–18. <http://dx.doi.org/10.1007/s12083-016-0511-y>.
- [10] M. Alsabaan, W. Alasmay, A. Albasir, K. Naik, Vehicular networks for a greener, *Environ.: a Surv.*, *IEEE Commun. Surv. Tutor.* 15 (2013) 1372–1388.
- [11] K.N. Qureshi, A.H. Abdullah, O. Kaiwartya, F. Ullah, S. Iqbal, A. Altameem, Weighted link quality and forward progress coupled with modified RTS/CTS for beaconless packet forwarding protocol (B-PFP) in VANETs, *Telecommun. Syst.* (2016) 1–16. <http://dx.doi.org/10.1007/s11235-016-0207-x>.
- [12] A.N. Hassan, O. Kaiwartya, A.H. Abdullah, D.K. Sheet, S. Prakash, Geometry based inter vehicle distance estimation for instantaneous GPS failure in VANETs. in: *Proceedings of the International Conference on Information and Communication Technology for Competitive Strategies*, ACM, pp. 72, Udaipur, India March, 2016.
- [13] O. Kaiwartya, S. Kumar, D.K. Lobiyal, P.K. Tiwari, A.H. Abdullah, A.N. Hassan, Multiobjective dynamic vehicle routing problem and time seed based solution using particle swarm optimization, *J. Sens.* 15 (2015) 1–14.
- [14] O. Kaiwartya, A.H. Abdullah, Y. Cao, R.S. Raw, S. Kumar, D.K. Lobiyal, I.F. Isnin, X. Liu, R.R. Shah, T-MQM: testbed-based multi-metric quality measurement of sensor deployment for precision agriculture—a case study, *IEEE Sens. J.* 16 (2016) 8649–8664.
- [15] O. Kaiwartya, S. Kumar, Guaranteed geocast routing protocol for vehicular ad hoc networks in highway traffic environment, *Wirel. Personal. Commun.* 83 (2015) 2657–2682.
- [16] S. Panichpapiboon, W. Pattara-atikom, A review of information dissemination protocols for vehicular ad hoc networks, *IEEE Commun. Surv. Tutor.* 14 (2012) 784–798.
- [17] S. Al-Sultan, M.M. Al-Doori, A.H. Al-Bayatti, H. Zedan, A comprehensive survey on vehicular ad hoc network, *J. Netw. Comput. Appl.* 37 (2014) 380–392.
- [18] R. Jiang, Y. Zhu, T. He, Y. Liu, L.M. Ni, Exploiting trajectory-based coverage for geocast in vehicular networks, *IEEE Trans. Parallel Distrib. Syst.* 25 (2014) 3177–3189.
- [19] O. Kaiwartya, S. Kumar, Enhanced caching for geocast routing in vehicular ad hoc network, in: D.P. Mohapatra, S. Patnaik (Eds.) *Intelligent Computing, Networking, and Informatics*, Proceedings of the International Conference on Advanced Computing, Networking, and Informatics, India, June 2013, Springer India, New Delhi, 2014, pp. 213–220.
- [20] V.N.G.J. Soares, J.J.P.C. Rodrigues, F. Farahmand, GeoSpray: a geographic routing protocol for vehicular delay-tolerant networks, *Inf. Fusion* 15 (2014) 102–113.
- [21] K. Shafiee, V.C.M. Leung, Connectivity-aware minimum-delay geographic routing with vehicle tracking in VANETs, *Ad Hoc Netw.* 9 (2011) 131–141.
- [22] M.D. Dikaiakos, A. Florides, T. Nadeem, L. Ifode, Location-aware services over vehicular ad-hoc networks using car-to-car communication, *IEEE J. Sel. Areas Commun.* 25 (2007) 1590–1602. <http://dx.doi.org/10.1109/JSAC.2007.071008>.
- [23] C.D.M. Cordeiro, H. Gossain, D.P. Agrawal, Multicast over wireless mobile ad hoc networks: present and future directions, *IEEE Netw.* 17 (2003) 52–59.
- [24] J. Lope, A survey of geographic routing protocols for vehicular ad hoc networks (VANETs), *New Mex. State Univ.* (2010) 1–15.
- [25] H. Zhu, M. Li, L. Fu, G. Xue, Y. Zhu, L.M. Ni, Impact of traffic influxes: revealing exponential intercontact time in urban vanets, *IEEE Trans. Parallel Distrib. Syst.* 22 (2011) 1258–1266.
- [26] The California Vehicle Activity Database (Cal-VAD). (<http://calvad.ctmlabs.net/>), 2014 (accessed 15 April 2014).
- [27] The US Department of transportation. (<https://www.fhwa.dot.gov/policyinformation/index.cfm>), 2014 (accessed 18 April 2014).
- [28] S. Barber, The UUCP Mapping Project, Network Working Group, Internet Draft. <https://tools.ietf.org/html/draft-barber-uucp-project-conclusion-00>, 2010.
- [29] C. Farrell, M. Schulze, S. Pleitner, D. Baldoni, DNS encoding of geographical location, 1994.
- [30] C. Davis, I. Dickinson, T. Goodwin, P. Vixie, A means for expressing location information in the domain name system, 1996.
- [31] G.G. Finn, Routing and Addressing Problems in Large Metropolitan-Scale Internetworks. ISI Research Report, 1987.
- [32] Y. Li, D. Jin, Z. Wang, P. Hui, L. Zeng, S. Chen, A markov jump process model for urban vehicular mobility: modeling and applications, *IEEE Trans. Mob. Comput.* 13 (2014) 1911–1926.
- [33] M. Jerbi, S.-M. Senouci, T. Rasheed, Y. Ghamri-Doudane, Towards efficient geographic routing in urban vehicular networks, *IEEE Trans. Veh. Technol.* 58 (2009) 5048–5059.
- [34] N. Kumar, J.-H. Lee, Peer-to-peer cooperative caching for data dissemination in urban vehicular communications, *IEEE Syst. J.* 8 (2014) 1136–1144.
- [35] W. Viriyasitavat, F. Bai, O.K. Tonguz, UV-CAST: an urban vehicular broadcast protocol, in: *Proceedings of Vehicular Networking Conference (VNC)*, 2010, IEEE, 2010, pp. 25–32.
- [36] R.S. Raw, S. Das, Performance analysis of P-GEDIR protocol for vehicular ad hoc network in urban traffic environments, *Wirel. Personal. Commun.* 68 (2013) 65–78.

- [37] Y. Zhu, R. Jiang, J. Yu, Z. Li, M. Li, Geographic routing based on predictive locations in vehicular ad hoc networks, *EURASIP J. Wirel. Commun. Netw.* 2014 (2014) 1–9.
- [38] K. Katsaros, R. Kernchen, M. Dianati, D. Rieck, C. Zinoviou, Application of vehicular communications for improving the efficiency of traffic in urban areas, *Wirel. Commun. Mob. Comput.* 11 (2011) 1657–1667.
- [39] I. Lequerica, P.M. Ruiz, V. Cabrera, Improvement of vehicular communications by using 3G capabilities to disseminate control information, *IEEE Netw.* 24 (2010).
- [40] O. Kaiwartya, S. Kumar, R. Kasana, Traffic light based time stable geocast (T-TSG) routing for urban VANETs, *Contemporary Computing (IC3)*, in: Proceedings of the Sixth International Conference on, IEEE, 2013, pp. 113–117.
- [41] R. Jiang, Y. Zhu, Coverage-aware geocast routing in urban vehicular networks, in: Proceedings of IEEE 26th International Parallel and Distributed Processing Symposium Workshops & PhD Forum (IPDPSW), 2012, pp. 2522–2525.
- [42] C. Li, C. Zhao, L. Zhu, H. Lin, J. Li, Geographic routing protocol for vehicular ad hoc networks in city scenarios: a proposal and analysis, *Int. J. Commun. Syst.* 27 (2014) 4126–4143.
- [43] J.-J. Chang, Y.-H. Li, W. Liao, C. Chang, Intersection-based routing for urban vehicular communications with traffic-light considerations, *IEEE Wirel. Commun.* 19 (2012).
- [44] E. Schoch, F. Kargl, M. Weber, Communication patterns in VANETs, *IEEE Commun. Mag.* 46 (2008).
- [45] G.A. Galaviz-Mosqueda, R. Aquino-Santos, S. Villarreal-Reyes, R. Rivera-Rodríguez, L. Villaseñor-González, A. Edwards, Reliable freestanding position-based routing in highway scenarios, *Sensors* 12 (2012) 14262–14291.
- [46] J. Karedal, N. Czink, A. Paier, F. Tufvesson, A.F. Molisch, Path loss modeling for vehicle-to-vehicle communications, *IEEE Trans. Veh. Technol.* 60 (2011) 323–328.
- [47] E. Baccelli, P. Jacquet, B. Mans, G. Rodolakis, Highway vehicular delay tolerant networks: information propagation speed properties, *IEEE Trans. Inf. Theory* 58 (2012) 1743–1756.
- [48] A. Fonseca, T. Vazão, Applicability of position-based routing for VANET in highways and urban environment, *J. Netw. Comput. Appl.* 36 (2013) 961–973.
- [49] Y.S. Chen, Y.W. Lin, A multicast routing protocol with carry-and-forward in vehicular ad hoc networks, *Int. J. Commun. Syst.* 27 (2014) 1416–1440.
- [50] G.Y. Chang, J.-P. Sheu, T.-Y. Lin, K.-Y. Hsieh, Cache-based routing for vehicular ad hoc networks in city environments, in: Proceedings of Wireless Communications and Networking Conference (WCNC), 2010, pp. 1–6.
- [51] O. Kaiwartya, S. Kumar, Cache agent-based geocasting in VANETs, *Int. J. Inf. Commun. Technol.* 7 (2015) 562–584.
- [52] J.A. Dias, J.J. Rodrigues, L. Zhou, Cooperation advances on vehicular communications: a survey, *Veh. Commun.* 1 (2014) 22–32.
- [53] O. Kaiwartya, S. Kumar, Guaranteed geocast routing protocol for vehicular ad hoc networks in highway traffic environment, *Wirel. Personal. Commun.* 83 (2015) 2657–2682.
- [54] W. Alasmary, W. Zhuang, Mobility impact in IEEE 802.11 p infrastructureless vehicular networks, *Ad Hoc Netw.* 10 (2012) 222–230.
- [55] M.A. Hoque, X. Hong, B. Dixon, Efficient multi-hop connectivity analysis in urban vehicular networks, *Veh. Commun.* 1 (2014) 78–90.
- [56] P. Neelakantan, A. Babu, Connectivity analysis of vehicular ad hoc networks from a physical layer perspective, *Wirel. Personal. Commun.* (2013) 1–26.
- [57] R.S. Raw, D. Lobiya, B-MFR routing protocol for vehicular ad hoc networks, in: Proceedings of International Conference on Networking and Information Technology (ICNIT), IEEE, 2010, pp. 420–423.
- [58] I. Stojmenovic, A.P. Ruhl, D. Lobiya, Voronoi diagram and convex hull based geocasting and routing in wireless networks, *Wirel. Commun. Mob. Comput.* 6 (2006) 247–258.
- [59] S. Bastani, B. Landfeldt, L. Libman, A traffic density model for radio overlapping in urban Vehicular Ad hoc Networks, in: Proceedings of the 36th IEEE Conference on Local Computer Networks (LCN), 2011, pp. 85–92.
- [60] C. Li, L. Wang, Y. He, C. Zhao, H. Lin, L. Zhu, A link state aware geographic routing protocol for vehicular ad hoc networks, *EURASIP J. Wirel. Commun. Netw.* 2014 (2014) 176.
- [61] P.R. Pereira, A. Casaca, J.J. Rodrigues, V.N. Soares, J. Triay, C. Cervelló-Pastor, From delay-tolerant networks to vehicular delay-tolerant networks, *IEEE Commun. Surv. Tutor.* 14 (2012) 1166–1182.
- [62] H. Ghafoor, K. Aziz, Position-based and geocast routing protocols in VANETs, in: Proceedings of the 7th International Conference on Emerging Technologies (ICET), IEEE, 2011, pp. 1–5.
- [63] R.S. Schwartz, H. Scholten, P. Havinga, A scalable data dissemination protocol for both highway and urban vehicular environments, *EURASIP J. Wirel. Commun. Netw.* 2013 (2013) 257.
- [64] J. Zhao, G. Cao, VADD: vehicle-assisted data delivery in vehicular ad hoc networks, *IEEE Trans. Veh. Technol.* 57 (2008) 1910–1922.
- [65] H. Okada, A. Takano, K. Mase, A proposal of link metric for next-hop forwarding methods in vehicular ad hoc networks, in: Proceedings of 6th IEEE Consumer Communications and Networking Conference, CCNC 2009, 2009, pp. 1–5.
- [66] M. Bilal, P.M. Chan, P. Pillai, Fastest-vehicle multi-hop routing in vehicular ad hoc networks, *Computer and Information Technology (CIT)*, in: Proceedings of the 10th IEEE International Conference on, 2010, pp. 773–778.
- [67] O. Kaiwartya, S. Kumar, Geocasting in vehicular ad hoc networks using particle swarm optimization, in: Proceedings of the International Conference on Information Systems and Design of Communication, ACM, 2014, pp. 62–66.
- [68] G. Yan, *Providing Location Security in Vehicular Ad Hoc Networks*, Old Dominion University, 2010.
- [69] F. Malandrino, C. Borgiattino, C. Casetti, C.-F. Chiasserini, M. Fiore, R. Sadao, Verification and inference of positions in vehicular networks through anonymous beaconing, *IEEE Trans. Mob. Comput.* 13 (2014) 2415–2428.
- [70] M.N. Meiri, J. Ben-Othman, M. Hamdi, Survey on VANET security challenges and possible cryptographic solutions, *Veh. Commun.* 1 (2014) 53–66.
- [71] O. Abumansoor, A. Boukerche, A secure cooperative approach for nonlinear-of-sight location verification in VANET, *IEEE Trans. Veh. Technol.* 61 (2012) 275–285.
- [72] M. Fogue, F.J. Martinez, P. Garrido, M. Fiore, C.-F. Chiasserini, C. Casetti, J.-C. Cano, C.T. Calafate, P. Manzoni, On the use of a cooperative neighbor position verification scheme to secure warning message dissemination in vanets, *Local Computer Networks (LCN)*, in: Proceedings of the 38th IEEE Conference on, 2013, pp. 276–279.
- [73] C. Chen, L. Liu, X. Du, X. Wei, C. Pei, Available connectivity analysis under free flow state in VANETs, *EURASIP J. Wirel. Commun. Netw.* 2012 (2012) 270.
- [74] C. Chen, Y. Jin, Q. Pei, N. Zhang, A connectivity-aware intersection-based routing in VANETs, *EURASIP J. Wirel. Commun. Netw.* 2014 (2014) 42.
- [75] V. Naumov, T.R. Gross, Connectivity-aware routing (CAR) in vehicular ad-hoc networks, in: Proceedings of the 26th IEEE International Conference on Computer Communications, INFOCOM 2007, pp. 1919–1927.
- [76] X. Zhang, L. Wu, Y. Zhang, Connectivity based on shadow fading and interference in wireless ad hoc networks, in: Proceedings of IEEE Wireless Communications and Networking Conference (WCNC), 2013, pp. 3782–3787.
- [77] R. Sollacher, M. Greiner, I. Glauche, Impact of interference on the wireless ad-hoc networks capacity and topology, *Wirel. Netw.* 12 (2006) 53–61.
- [78] O. Dousse, F. Baccelli, P. Thiran, Impact of interferences on connectivity in ad hoc networks, *IEEE/ACM Trans. Netw.* (TON) 13 (2005) 425–436.
- [79] C.M. Huang, S.Y. Lin, C.Y. Lin, A split reliable transport protocol over the vehicular ad hoc network communication environment, *Wirel. Commun. Mob. Comput.* 15 (2015) 2191–2205.
- [80] A. Cardote, Transport protocol for vehicular environments: challenges and trends, *Electron. Telecom.* 5 (2010) 202–207.
- [81] R. Schmitz, A. Leiggener, A. Festag, L. Eggert, W. Effelsberg, Analysis of path characteristics and transport protocol design in vehicular ad hoc networks, in: Proceedings of IEEE 63rd Vehicular Technology Conference, 2006. VTC 2006-Spring, 2006, pp. 528–532.
- [82] M. Bechler, S. Jaap, L. Wolf, An optimized tcp for internet access of vehicular ad hoc networks, in: Proceedings of NETWORKING 2005. Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems, 2005, pp. 869–880.
- [83] S. Tsiachris, G. Koltsidas, F.-N. Pavlidou, Junction-based geographic routing algorithm for vehicular ad hoc networks, *Wirel. Personal. Commun.* (2013) 1–19.
- [84] P. Sermpezis, G. Koltsidas, F.-N. Pavlidou, Investigating a junction-based multipath source routing algorithm for VANETs, *IEEE Commun. Lett.* 17 (2013) 600–603.
- [85] H. Saleet, R. Langar, K. Naik, R. Boutaba, A. Nayak, N. Goel, Intersection-based geographical routing protocol for VANETs: a proposal and analysis, *IEEE Trans. Veh. Technol.* 60 (2011) 4560–4574.
- [86] J. Toutouh, J. García-Nieto, E. Alba, Intelligent OLSR routing protocol optimization for VANETs, *IEEE Trans. Veh. Technol.* 61 (2012) 1884–1894.
- [87] M. Al-Rabayah, R. Malaney, A new scalable hybrid routing protocol for VANETs, *IEEE Trans. Veh. Technol.* 61 (2012) 2625–2635.